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Reducing Residential Peak Electricity Demand with Mechanical Pre-Cooling of Building Thermal Mass

William J.N. Turner, Jordan Roux & Iain S. Walker

Environmental Energy Technologies Division

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ABSTRACT

This study used an advanced airflow, energy and humidity modelling tool to evaluate the potential for residential mechanical pre-cooling strategies to reduce peak electricity demand. Simulations were performed for a typical new home in all US DOE Climate Zones. The results show that the effectiveness of pre-cooling is highly dependent on climate zone and the selected pre-cooling strategy. The expected energy trade-off between cooling peak energy savings and increased off-peak energy use is also shown. Best pre-cooling results for most climates were obtained using a short pre-cooling time window with a high pre-cooling set point temperature. All pre-cooling strategies caused the annual cooling energy demand of the simulated buildings to increase. However, pre-cooling for long time periods with a low temperature set point can eliminate up to 97% of the annual peak cooling load of the building.

KEYWORDS

Pre-Cooling, Air Conditioning, Mechanical Cooling, Peak Demand, Thermal Mass

1. Introduction

According to the US Energy Information Administration, 97 million US households had air conditioning in 2009, compared with 74 million households in 1997 (US EIA 1997; US EIA 2009). This increasing use of residential air conditioning is placing a large strain on electricity distribution grids. During particularly extreme weather, the extra cooling load can cause electricity demand to outstrip supply, leading to wide-spread blackouts such as those seen in the Northeast of the United States in 2003. Consequently there is currently a drive toward reducing the maximum instantaneous load on power grids. 'Peak energy demand' refers to the time of day when loads on the electricity distribution infrastructure reach a maximum. During the summer months this tends to happen between 16:00 and 20:00 when high outdoor temperatures coincide with people returning home from work, resulting in high residential air-conditioner use.

During peak periods the extra demand on the grid is met by increasing capacity via the operation of power plants with a higher marginal cost and CO_2 emissions than power plants used to meet base load. This increases the generation cost for each kilowatt-hour for the utility company. The cost is then passed down to the consumer in increased utility rates. Utility companies in the US are beginning to offer tariff-based incentives to consumers to help reduce peak energy demand and hence cost. An example of an incentive is 'Time of Use' (TOU) schemes, where a schedule is set by the utility company offering cheaper energy prices during off peak times and more expensive energy during peak times. This encourages consumers to shift their main energy use to periods when energy generation is less expensive and the overall demand may be met more easily. Other mechanisms for reducing the peak energy demand include solar shading, adoption of photovoltaics, load shedding (reducing total electricity use) and load shifting (moving electricity use to other parts of the day). Reductions in peak cooling demand have been demonstrated (numerically) possible by either increasing the amount of thermal insulation used within a wall (Al-Sanea & Zedan 2011), or by increasing the thermal mass of the wall (Al-Sanea et al. 2012).

Pre-cooling is a strategy that attempts to remove some of the increased peak demand on the electricity grid by shifting the cooling load to non-peak times. The cooling thermostat set points are reduced in the period preceding the peak period in order to force the air-conditioner to switch on. This cools the thermal mass of the house while electricity prices and generation costs are lower. The set points are then raised during the peak period. As the building takes time to warm up, the operation of the cooling equipment is delayed during the hot peak period. Additionally, the efficiency of air-conditioners (Energy Efficiency Ratio or EER) increases with lower outdoor temperatures, so their energy consumption is less while operating during off-peak periods. Using the thermal mass of a building to impact cooling (and heating) loads can be exploited to reduce costs, but this requires intelligent control of the building HVAC systems (Kim 2013).

Many studies have shown that cooling thermal mass can reduce the cooling load of commercial buildings (Rabi & Norford 1991; Snyder & Newell 1990; Braun 2003; Xu et al. 2004; Lee & Braun 2008; Yin et al. 2010; Corgnati & Kindinis 2007). However, there is very limited literature on pre-cooling residential buildings, and the work that has been done is typically restricted in scope to the climate of California. Beutler (2003) demonstrated via simulation that pre-cooling using mechanical air-conditioning could reduce annual peak period residential air-conditioner operation by between 75% and 84% in California. Simulation results from a study by the Davis Energy Group for a US utility company in California suggested that, when combined with night ventilation, pre-cooling could save up to 97% of residential peak electricity consumption (Davis Energy Group 2007). Although total annual electricity consumption increased by 26%, field testing from the same study yielded annual electrical peak savings of 88%. This is in agreement with Katipamula and Lu (2006) who also showed using a simplified building electricity load model, that precooling residences can reduce peak cooling loads, but at the expense of more total energy used.

This study looks at the potential for mechanical air-conditioner pre-cooling to reduce the peak electricity load and energy consumption of residential buildings. A computer modelling approach was used to study the load reduction of several cooling strategies in 15 different US climates. Due to the diversity in US climates, the results presented in this paper are applicable to a large range of countries and so fill a gap in the existing literature. The results of the simulations were used to assess the balance between peak energy reductions and off-peak energy consumption, while still providing good thermal comfort and indoor air quality (IAQ).

2. Simulations

In this study, the REGCAP building simulation tool was used to investigate the peak cooling energy demand reduction potential of mechanical pre-cooling. For each simulation there was a reference case used to determine the effect of the mechanical pre-cooling. The reference case was a house with continuous whole-house mechanical exhaust ventilation (typical of new construction in the US) and no mechanical pre-cooling using the air conditioner. The air conditioner ran to the standard operating set points (see Table 4) and infiltration effects were included in the ventilation rate of the house.

2.1. Building Simulation Tool

The energy consumption of the modeled houses was evaluated using the REGCAP residential building simulation tool. The REGCAP model, developed and validated at the University of Alberta (Walker 1993) and Lawrence Berkeley National Laboratory (Walker & Sherman 2007), is a residential HVAC model that combines ventilation, heat transfer, and moisture models to determine annual residential energy use as a function of building characteristics and location, and has been used in previous studies e.g., Turner et al. (2013). REGCAP was specifically written to assess residential HVAC systems and control strategies. The attic volume and house volume are treated as two separate well-mixed zones (mixing occurs instantaneously), but connected for airflow and heat transport. Energy, mass and moisture are conserved and flows are calculated iteratively. Once convergence criteria have been satisfied the simulation moves onto the next time step. REGCAP includes heating and cooling system airflows to and from the house and, via duct leakage, the attic. REGCAP also allows the modelling of distributed envelope leakage and mechanical system airflows for ventilation, heating and cooling, as well as individual localized leaks.

Key REGCAP inputs are building air leakage characteristics (total leakage and leakage distribution), time resolved weather data, weather shielding factors, building and HVAC equipment properties, and auxiliary fan schedules. Simulations were performed with a one-minute time resolution for a calendar year. The one-minute time-steps are important because they allow for fine time control of fans and heating/cooling equipment. It also means that house and HVAC system thermal mass effects can be captured, so that no assumptions are required for part-load effects and there is finer control of indoor temperatures by the thermostat.

REGCAP has been extensively verified and been shown to predict HVAC equipment energy consumption within 4% of measured systems. Ventilation rates are predicted within approximately 5% over a wide range of house leakage distributions and weather conditions (Wilson & Walker 1992a; Wilson & Walker

1992b; Siegel 1999; Walker et al. 1999; Siegel et al. 2000; Walker et al. 2002; Walker et al. 2005; Walker & Sherman 2007).

2.2. Climate Zones

Simulations were performed for all DOE climate zones (1 – 8) using TMY3 weather data (Wilcox & Marion 2008) for their representative cities (see Figure 1 and Table 1) (Briggs et al. 2003).

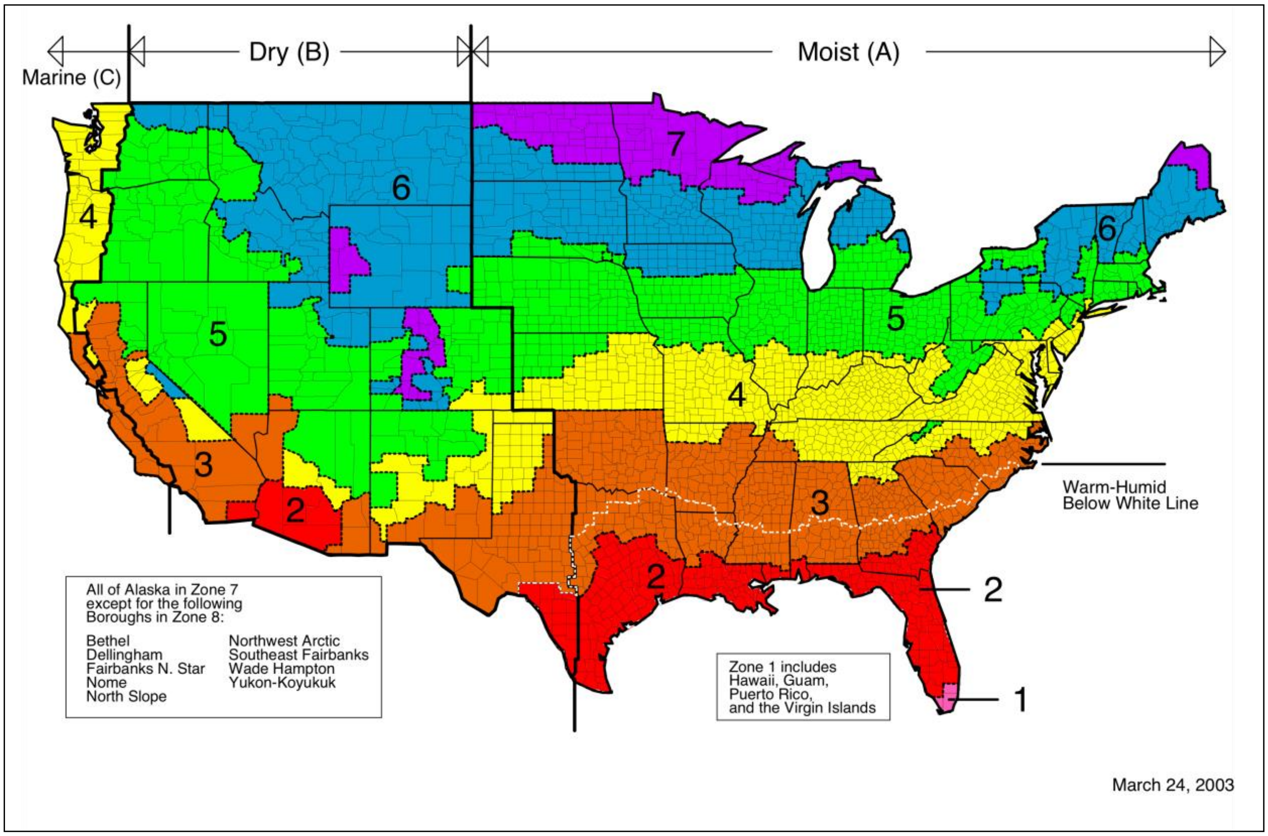

Figure 1: IECC Climate Zones for the United States (Briggs et al. 2003)

Table 1: IECC Climate Zones with definitions(Briggs et al. 2003)

Climate Zone	Representative City	State	Temp	Moisture	Köppen Classification Description
1A	Miami	FL	Very Hot	Humid	Tropical Wet-and-Dry
2A	Houston	TX	Hot	Humid	Humid Subtropical (Warm Summer)
2B	Phoenix	AZ	Hot	Dry	Arid Subtropical
3A	Memphis	TN	Warm	Humid	Humid Subtropical (Warm Summer)
3B	El Paso	TX	Warm	Dry	Semiarid Middle Latitude/Arid Subtropical/Highlands
3C	San Francisco	CA	Warm	Marine	Dry Summer Subtropical (Mediterranean)
4A	Baltimore	MD	Mixed	Humid	Humid Subtropical/Humid Continental (Warm Summer)
4B	Albuquerque	NM	Mixed	Dry	Semiarid Middle Latitude/Arid Subtropical/Highlands
4C	Salem	OR	Mixed	Marine	Marine (Cool Summer)
5A	Chicago	IL	Cool	Humid	Humid Continental (Warm Summer)
5B	Boise	ID	Cool	Dry	Semiarid Middle Latitude/Highlands
6A	Burlington	VT	Cold	Humid	Humid Continental (Warm Summer/Cool Summer)
6B	Helena	MT	Cold	Dry	Semiarid Middle Latitude/Highlands
7	Duluth	MN	Very Cold	-	Humid Continental (Cool Summer)
8	Fairbanks	AK	Subarctic	-	Subarctic

2.3.House Construction

House geometry was based on the California State Energy Code Title 24 Prototype C (Nittler & Wilcox 2008), which is a reasonably performing new home (Figure 2). It is better than most existing homes, but not a high performance home like those found in the Building America program. It has an occupied living area of 195 m^2 (2,100 ft^2) with uniform 2.5 m (8.2 ft) ceilings, and a volume of 488 m^3 (17,220 ft^3). The house was simulated to contain four occupants with three bedrooms, three bathrooms and one kitchen. Envelope leakage was 4.8 ACH_{50}, typical of new construction, based on recent studies by Offerman (2009) and Wilcox (2011).

Figure 2: The Title 24 housing Prototype C, with 195 m2 occupied floor area

Glazing and insulation values for ceilings, walls and air ducts can be found in Table 2. The R-value used for insulation ratings in the US is equivalent to the inverse of the U-value used in Europe i.e. R30 is equivalent to a U-value of 0.033 W/m^2K.

Table 2: House Insulation Levels from IECC (2009) Table 402.1.1

Climate Zone	Representative City	Glazing		Ceiling	Walls	Ducts Outside Conditioned Space
		U-Value	SHGC			
1A	Miami, FL	0.65	0.3	R30	R13	R8
2A	Houston, TX	0.65	0.3	R30	R13	R8
2B	Phoenix, AZ	0.65	0.3	R30	R13	R8
3A	Memphis, TN	0.50	0.3	R30	R13	R8
3B	El Paso, TX	0.50	0.3	R30	R13	R8
3C	San Francisco, CA	0.50	0.3	R30	R13	R8
4A	Baltimore, MD	0.35	0.3	R38	R13	R8
4B	Albuquerque, NM	0.35	0.3	R38	R13	R8
4C	Salem, OR	0.35	0.3	R38	R20	R8
5A	Chicago, IL	0.35	0.3	R38	R20	R8
5B	Boise, ID	0.35	0.3	R38	R20	R8
6A	Burlington, VT	0.35	0.3	R49	R20	R8
6B	Helena, MT	0.35	0.3	R49	R20	R8
7	Duluth, MN	0.35	0.3	R49	R21	R8
8	Fairbanks, AK	0.35	0.3	R49	R21	R8

2.4. Internal Loads

The house was assumed to be unoccupied between the hours of 08:00 and 16:00 every weekday, and then occupied for the rest of the time by four occupants. The daily latent heat gain from moisture generation followed the approach used previously by Walker and Sherman (2006; 2007). The moisture generation rates are based on ASHRAE Standard 160P (ASHRAE 2009) with corrections for kitchen and bathroom exhaust using the bathing, cooking and dishwashing estimates from Emmerich et al. (2005) (see Table 3). It was assumed that all kitchen and bathroom-generated moisture was vented directly to outside using exhaust fans.

For the daily sensible heat gain from lights, appliances, people and other sources, the Title 24 ACM (CEC 2010) value of 5.9 kWh/day (20,000 Btu/day) for each dwelling unit, plus 0.0044 kWh/day (15 Btu/day) for each square foot of conditioned floor area was used. For the simulated house this meant a sensible load of 630 W and a moisture net generation rate of 9.8 kg/day (21.5lb/day). Loads were not altered for seasonal adjustments.

Table 3: Internal occupancy based moisture generation rates from ASHRAE Standard 160P and Emmerich et al. (2005)

Number of Occupants	Moisture Generation Rate [kg/day]	Bathing, Cooking and Dishwashing [kg/day]	Net Generation Rate [kg/day]
2	7.8	3.2	4.6
3	12.1	3.6	8.5
4	13.8	4.0	9.8
5	14.7	4.4	10.3

2.5.HVAC Equipment

Heating and cooling equipment was sized according to ACCA Manuals J & S (ACCA 2006). For heating we used a minimally efficient 80% AFUE natural gas furnace. For cooling, we used a SEER 13 split-system air conditioner with a TXV refrigerant flow control. Heating and cooling ducts were located in the unconditioned attic. The total duct leakage was 6%, evenly split between 3% supply leakage and 3% return leakage.

Whole-house ventilation was provided by an ASHRAE Standard 62.2-compliant extract fan operating continuously at 28 l/s (60 cfm). Additional ventilation was provided by an extract fan in each bathroom (24 l/s or 51 cfm), a kitchen range hood (47 l/s or 100 cfm) and a clothes dryer (71 l/s or 150 cfm). The above devices would operate to a schedule defined by the building occupants. Bathroom fans operated for a total of 40 minutes per person per day, split across different times of day. The kitchen range hood operated for one hour per day between 17:30 and 18:30. On weekends there was an additional 30 minutes of operation in the morning between 09:30 and 10:00. The clothes dryer operated during two laundry days each week for three consecutive hours.

2.6.Mechanical Pre-Cooling

Pre-cooling was simulated by reducing the cooling thermostat set points during the pre-peak time periods. A thermostat with set-point temperatures depending on time-of-day was used (Table 4). An initial set of reference simulations were run with no pre-cooling so that the effect of pre-cooling could be quantified. Two pre-cooling set point temperatures were used, combined with three different lengths of pre-cooling (windows). The chosen pre-cooling set points of 22.2°C and 23.3°C both represent indoor temperatures acceptable for thermal comfort (Olesen 2000). The pre-cooling windows were 8 (long), 6 (medium) and 4 (short) hours in length. All pre-cooling windows ended at the beginning of the cooling peak period (16:00 until 20:00). To summarise:

- There were two pre-cooling thermostat temperatures of 22.2°C and 23.3°C (72°F and 74°F)
- Pre-cooling windows were:
    - 08:00 to 16:00 (long – 8 hours)
    - 11:00 to 16:00 (medium – 5 hours)
    - 13:00 to 16:00 (short – 3 hours)
- The cooling peak period was defined as 16:00 to 20:00 (4 hours in length)

The baseline thermostat set points used in the simulations for the heating and cooling equipment are shown in Table 4. These were then changed according to the pre-cooling regimes above.

Table 4: Thermostat Set Points

Time		Heating		Cooling	
Start	End	°C	°F	°C	°F
0:00	1:00	20.0	68	25.0	77
1:00	2:00	20.0	68	25.0	77
2:00	3:00	20.0	68	25.0	77
3:00	4:00	20.0	68	25.0	77
4:00	5:00	20.0	68	25.0	77
5:00	6:00	20.0	68	25.0	77
6:00	7:00	20.0	68	25.0	77
7:00	8:00	21.1	70	26.7	80
8:00	9:00	21.1	70	26.7	80
9:00	10:00	21.1	70	26.7	80
10:00	11:00	21.1	70	26.7	80
11:00	12:00	21.1	70	26.7	80
12:00	13:00	21.1	70	26.7	80
13:00	14:00	21.1	70	26.7	80
14:00	15:00	21.1	70	26.7	80
15:00	16:00	21.1	70	26.7	80
16:00	17:00	21.1	70	25.0	77
17:00	18:00	21.1	70	25.0	77
18:00	19:00	21.1	70	25.0	77
19:00	20:00	21.1	70	25.0	77
20:00	21:00	21.1	70	25.0	77
21:00	22:00	21.1	70	25.0	77
22:00	23:00	21.1	70	25.0	77
23:00	0:00	20.0	68	25.0	77

Note for climate zones 1A and 2A (the humid climates of Miami, FL and Houston, TX) the cooling set point was set to a constant 23.3°C (74°F) to represent more realistically how air conditioners are used to maintain indoor temperature and reduce the humidity. Consequently these climates exhibit higher energy use than if the set points in Table 4 were used.

3. Results and Discussion

Below will be discussed the potential for peak demand reductions using mechanical pre-cooling. While the study was performed for homes in the US, the range of climates that are covered in the US mean that the results may be applied to other regions and countries.

The home under study was of lightweight wood-frame construction. Although this is typical of the majority of new home construction in the US, homes built from brick or block with higher thermal mass may have different optimum results due to the longer time constants associated with heating and cooling the structures. The issue of higher mass homes should be addressed in future work.

3.1. Indoor Air Temperature

Figure 3 shows simulated pre-cooling results for one 24-hour period in climate zone 3B (El Paso, TX). The indoor air temperature is plotted for the three different pre-cooling regimes. The reference case (blue line) has no pre-cooling and so the indoor air temperature rises to the indoor set point just after midday when the air-conditioner turns on. The long pre-cooling period (red line) shows the air-conditioner turning on at 08:00 and maintaining the house temperature at around 22.2°C up until the peak period begins at 16:00. Then the thermostat set point increases and the air-conditioner switches off. In this case the air-conditioner remains switched off until around 18:00 so 50% of the cooling peak load was removed. The green and purple lines show the medium (11:00 to 16:00) and short (13:00 to 16:00) pre-cooling periods respectively. The indoor temperature for the medium pre-cooling case is the same at the start of the peak period (16:00) as for the long pre-cooling case. This indicates that the longer pre-cooling period was unnecessary because the air conditioner was sized so that it could reduce the internal air temperature to the same point in both long and medium cases. The short pre-cooling period only brings the indoor temperature down to 24.3°C in the time available, and so the air conditioner switches back on around one hour into the peak period.

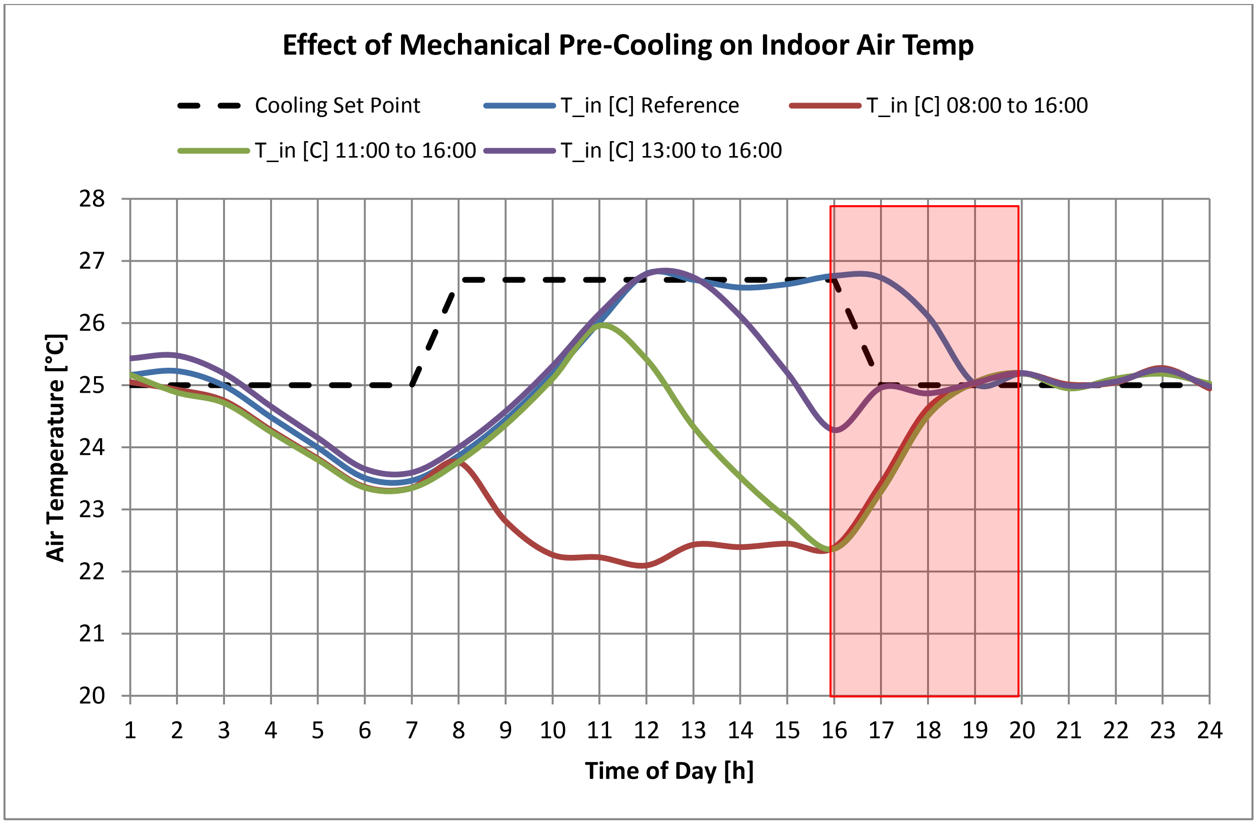

Figure 3: Effect on indoor air temperature of changing the cooling set points at different times to produce pre-cooling. 22.2°C or 72°F set point used, climate zone 3B – El Paso, TX. The dashed line shows the standard (no pre-cooling) cooling set point temperatures throughout the day. The red box indicates the peak period.

3.2. Total Annual Energy Consumption

Table 5 shows the energy impacts of pre-cooling in Climate Zone 1A (Miami, FL).

- $|\Delta E_P|$ is the peak period energy reduction, calculated by summing the air-conditioner energy during all of the cooling peak periods with no pre-cooling, and then subtracting the air-conditioner energy consumed during the coincident time periods from the simulations with pre-cooling. The magnitude is used as the energy difference will be negative

- R is $|\Delta E_P|$ expressed as a percentage
- ΔE_C is the increase in off-peak cooling energy (i.e. energy penalty) during the year from operating the air-conditioner under a pre-cooling schedule
- Γ is the 'peak-to-penalty' energy ratio. (See below).

Table 5: Pre-cooling results for Climate Zone 1A (Miami, FL)

Pre-Cooling Set Points [°C]	Pre-Cooling Windows	Annual Cooling Energy [kWh]	Annual Peak Energy [kWh]	Peak Period Energy Reduction, $|\Delta E_p|$ [kWh]	Peak Period Energy Reduction, R [%]	Increase in Off-Peak Cooling Energy, ΔE_C [kWh]	Peak-to-Penalty Ratio, Γ ($|\Delta E_p|$/ ΔE_C)
N.A.	N.A	4,980	2,150	N.A.	N.A.	N.A.	N.A.
22.2	08:00 to 16:00	8,450	70	2080	97	3470	0.60
22.2	11:00 to 16:00	7,600	70	2080	97	2620	0.79
22.2	13:00 to 16:00	6,600	60	2090	97	1620	1.29
23.3	08:00 to 16:00	6,440	290	1860	86	1460	1.27
23.3	11:00 to 16:00	6,110	290	1860	87	1130	1.65
23.3	13:00 to 16:00	5,670	300	1850	86	690	2.68

It can be seen that in Miami, pre-cooling always increases the total cooling energy used by the house, under all pre-cooling temperature set points and time windows. Using the pre-cooling temperature set point of 22.2°C with the longest pre-cooling window (08:00 to 16:00) increases the annual cooling energy from 4,975 kWh to 8,447 kWh. However, the amount of cooling energy used during the cooling peak periods was reduced over the entire year by 97%.

Table 6 shows the annual increase in off-peak cooling energy ΔE_C for all climate zones. The simulated pre-cooling strategies always increased the total amount of cooling energy used over the year. The anomalously high values for Climate Zones 3C and 8 are an artefact of the near-zero cooling demand of the climates (San Francisco, CA and Fairbanks, AK).

Table 6: Increase in off-peak cooling energy ΔE_C [%] compared with the baseline case with no pre-cooling.

CZ & Reference City	ΔE_C [%]: 22.2°C			ΔE_C [%]: 23.3°C		
	Long	Medium	Short	Long	Medium	Short
1A. Miami, FL	170%	153%	133%	129%	123%	114%
2A. Houston, TX	137%	128%	119%	123%	118%	112%
2B. Phoenix, AZ	124%	116%	109%	109%	107%	104%
3A. Memphis, TN	133%	125%	117%	120%	115%	110%
3B. El Paso, TX	132%	127%	118%	117%	114%	110%
3C. San Francisco, CA	869%	869%	850%	250%	250%	250%
4A. Baltimore, MD	149%	140%	129%	127%	122%	115%
4B. Albuquerque, NM	142%	137%	127%	122%	120%	114%
4C. Salem, OR	168%	167%	164%	117%	117%	115%
5A. Chicago, IL	168%	167%	164%	117%	117%	115%
5B. Boise, ID	127%	125%	122%	112%	112%	111%
6A. Burlington, VT	132%	126%	118%	119%	115%	109%
6B. Helena, MT	157%	158%	154%	117%	117%	116%
7. Duluth, MN	198%	191%	181%	126%	123%	120%
8. Fairbanks, AK	244%	244%	244%	116%	116%	116%

$\Delta E_C \leq 125$
$125 < \Delta E_C \leq 150$
$150 < \Delta E_C \leq 200$
$200 < \Delta E_C$

3.3. Peak Period Energy Reductions

The peak period energy reductions ($|\Delta E_P|$) are shown in Table 7. Most peak period energy savings are to be had in the warmer climate zones of 1A, 2A, 2B, 3A and 3B where mechanical cooling is most prolific. The most peak energy saved is 2,080 kWh in climate zone 1A (Miami, FL). Peak savings are still possible in the climate zones with warm summers such as 4A (Baltimore, MD) and 4B (Albuquerque, NM). Obviously, the climate zones with very little air-conditioning use (e.g. 3C San Francisco, CA and 8 Fairbanks, AK) see the lowest peak energy reductions.

Table 7: Total annual peak period cooling energy reductions, |ΔE_P| [kWh], compared to the baseline case with no pre-cooling (Peak Period = 16:00 to 20:00). Long, medium and short are the pre-cooling lengths (8 hours, 5 hours and 3 hours respectively).

	|ΔE_P| [kWh]: 22.2°C			|ΔE_P| [kWh]: 23.3°C		
CZ & Reference City	**Long**	**Medium**	**Short**	**Long**	**Medium**	**Short**
1A. Miami, FL	2,080	2,080	2,080	1,860	1,860	1,850
2A. Houston, TX	1,960	1,910	1,670	1,780	1,780	1,620
2B. Phoenix, AZ	1,620	1,610	1,520	1,280	1,280	1,260
3A. Memphis, TN	1,010	960	790	860	850	750
3B. El Paso, TX	1,140	1,130	1,070	920	920	910
3C. San Fran, CA	10	10	10	10	10	10
4A. Baltimore, MD	640	590	470	580	550	460
4B. Albuquerque, NM	630	570	450	540	510	420
4C. Salem, OR	160	160	140	120	120	110
5A. Chicago, IL	370	330	280	370	330	280
5B. Boise, ID	400	390	350	300	300	270
6A. Burlington, VT	630	550	430	600	530	430
6B. Helena, MT	180	180	180	120	130	130
7. Duluth, MN	80	70	60	70	60	50
8. Fairbanks, AK	20	20	20	10	10	10

$1500 \leq \Delta E_P$
$1000 \leq \Delta E_P < 1500$
$500 \leq \Delta E_P < 1000$
$\Delta E_P < 500$

3.4. Fractional Peak Period Energy Reductions

The fractional peak period energy reductions (R) are shown in Table 8. Pre-cooling to 22.2°C can remove 97% of the annual peak period cooling energy in Climate Zone 1A (Miami, FL). Generally, the longer the pre-cooling period and the lower the pre-cooling set point temperature the larger the cooling peak period energy savings. However, these are offset by the increased energy consumption during the pre-cooling periods when the air-conditioner would not normally be running. The averages across all climate zones for the 22.2°C set points are 86% for the long pre-cooling window, 82% for the medium and 74% for the short. For the higher 23.3°C set point the averages are 72% for the long, 70% for the medium and 64% for the short windows.

Table 8: Fractional peak period energy reductions, R [%], compared to the baseline case with no pre-cooling.

	R [%]: 22.2°C			R [%]: 23.3°C		
CZ & Reference City	Long	Medium	Short	Long	Medium	Short
1A. Miami, FL	97	97	97	86	87	86
2A. Houston, TX	91	89	78	84	83	75
2B. Phoenix, AZ	59	59	56	47	47	46
3A. Memphis, TN	90	85	71	77	76	67
3B. El Paso, TX	85	84	80	69	69	68
3C. San Francisco, CA	84	84	84	57	57	57
4A. Baltimore, MD	93	85	69	83	80	66
4B. Albuquerque, NM	87	78	62	73	69	58
4C. Salem, OR	83	82	70	61	61	56
5A. Chicago, IL	90	81	69	89	79	67
5B. Boise, ID	77	75	66	57	56	51
6A. Burlington, VT	78	68	54	75	66	53
6B. Helena, MT	91	91	90	65	65	65
7. Duluth, MN	86	77	63	79	70	57
8. Fairbanks, AK	96	96	96	81	81	81

90 ≤ R
80 ≤ R < 90
70 ≤ R < 80
R < 70

3.5. Peak-to-Penalty Energy Ratio

In order to quantify the pre-cooling trade-off between peak period energy saved and extra off-peak energy used, the 'peak-to-penalty' ratio, Γ, is introduced. It is the ratio between the magnitude of the peak period energy reduction (i.e. peak period energy saved), ΔE_P, and the increase in off-peak cooling energy (i.e. energy penalty), ΔE_C, used during the year from operating the air-conditioner when it would not normally be running (see Figure 4). The ratio Γ increases as the peak period energy reduction gets larger while the off-peak energy penalty gets lower:

$$\boldsymbol{\Gamma} = \frac{|\boldsymbol{\Delta E_P}|}{\boldsymbol{\Delta E_C}} \qquad \text{Equation 1}$$

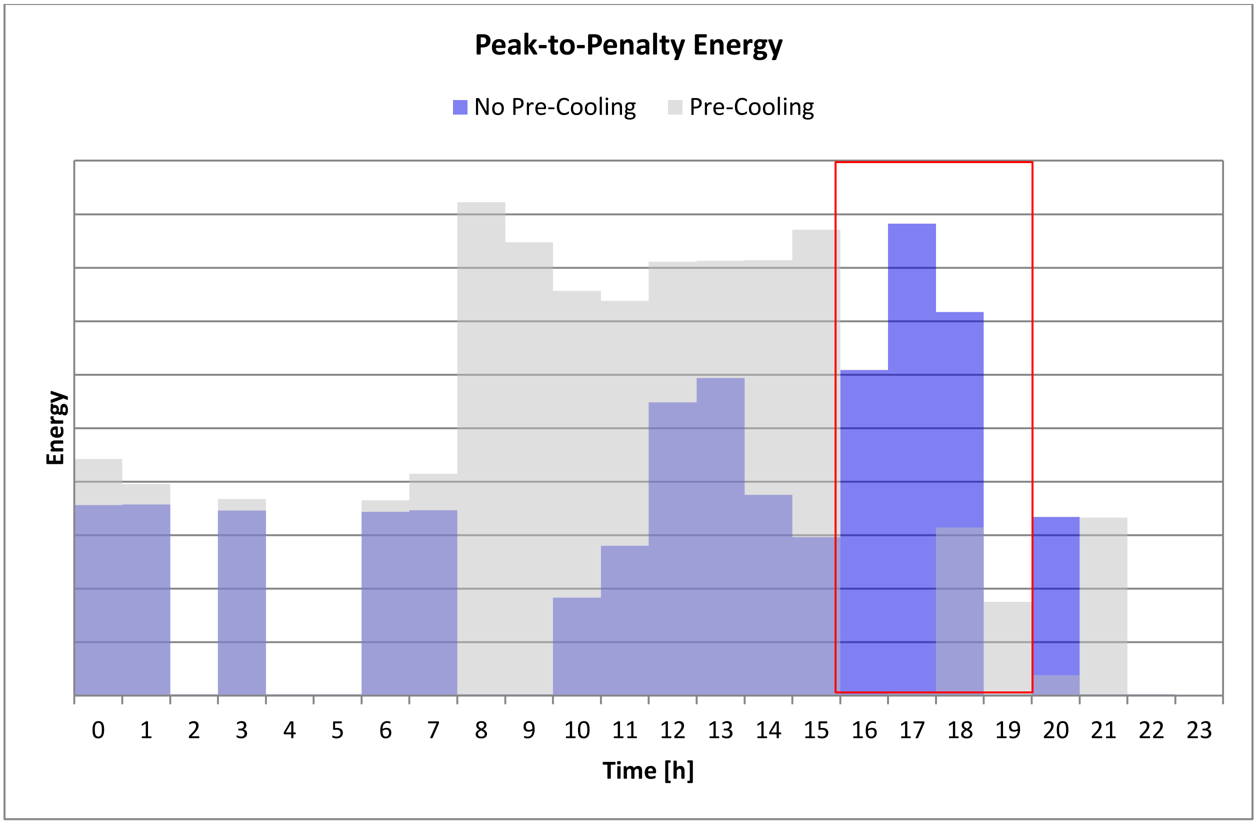

Figure 4: The purple area represents the average hourly building energy use with no pre-cooling. The grey area represents the energy use with pre-cooling. $|\Delta E_P|$ is the magnitude of the difference between the purple area and the grey area during the peak period (red box). ΔE_C is the difference between the purple area and the grey area outside the peak period.

Table 9 shows the peak-to-penalty energy ratio for the different pre-cooling strategies. It is generally highest for the shorter pre-cooling periods with the higher thermostat set point of 23.3°C. Γ decreases as the pre-cooling time periods get longer and the pre-cooling set point gets lower. The rate of change of Γ is non-linear with time, suggesting that shorter, warmer pre-cooling periods are more efficient at removing peak load, although they remove less peak load in total. In terms of guiding selection of an optimum pre-cooling strategy, it is necessary to select the greatest cooling peak energy savings that have the least off-peak energy penalties. Because the range of cooling peak period energy savings for a given climate is not very large, for most cases the higher pre-cooling temperature set point and shorter cooling windows are optimum. Climates with less annual air-conditioning use showed better results for the long pre-cooling window and higher temperature set point. Only Climate Zone 3C showed no advantage with pre-cooling strategies due to the near-zero cooling demand of the climate.

Table 9: Peak-to-Penalty energy ratio for all 15 climate zones

	Γ : 22.2°C			Γ : 23.3°C		
Reference City	Long	Medium	Short	Long	Medium	Short
1A. Miami, FL	0.60	0.79	1.29	1.27	1.65	2.68
2A. Houston, TX	1.55	2.02	2.60	2.30	2.96	4.16
2B. Phoenix, AZ	0.94	1.38	2.37	1.93	2.67	4.49
3A. Memphis, TN	1.21	1.52	1.85	1.69	2.18	2.99
3B. El Paso, TX	1.38	1.64	2.29	2.12	2.51	3.67
3C. San Francisco, CA	0.10	0.10	0.11	0.37	0.37	0.37
4A. Baltimore, MD	1.16	1.28	1.44	1.86	2.21	2.74
4B. Albuquerque, NM	1.27	1.31	1.40	2.04	2.20	2.56
4C. Salem, OR	0.95	0.96	0.86	2.88	2.88	2.93
5A. Chicago, IL	0.85	0.86	0.91	1.72	1.76	1.87
5B. Boise, ID	2.15	2.23	2.22	3.52	3.60	3.64
6A. Burlington, VT	1.32	1.43	1.66	2.18	2.45	3.05
6B. Helena, MT	1.35	1.33	1.42	3.25	3.29	3.47
7. Duluth, MN	0.61	0.58	0.53	2.08	2.10	1.98
8. Fairbanks, AK	0.43	0.43	0.43	3.07	3.07	3.07

$\Gamma \leq 1$
$1 < \Gamma \leq 2$
$2 < \Gamma \leq 3$
$3 \leq \Gamma$

3.6. Potential Carbon Savings

The net effect of mechanical pre-cooling using the air conditioner is always to increase the total annual energy use of the house. However, by removing peak loads the need for running higher carbon producing power plants during peak periods (in some US States but not all) can be reduced. This means that the net carbon output can be reduced, even though more energy is used. Further work and investigation would be required to verify this.

4. Conclusions & Recommendations

The potential for reducing peak cooling energy demand by using mechanical pre-cooling was investigated. Mechanical pre-cooling was achieved by running the air-conditioner at lower temperature set points than usual, before the peak cooling demand period. Different pre-cooling time periods and temperature set points were explored.

The results are summarized as follows:

- Mechanical pre-cooling using the air conditioner can remove up to 97% of the peak cooling load at the settings tested. This is heavily dependent on climate zone, the length of the pre-cooling period and the pre-cooling set point
- In order to maximize peak cooling energy savings while using the least amount of cooling energy, the high cooling climates (zones 1A-3B) should use a short pre-cooling time window (4 hours) with the highest pre-cooling temperature set point (23.3°C or 74°F)
- Climates with less cooling demand should use the higher pre-cooling temperature set point (23.3°C or 74°F), but the length of the pre-cooling period becomes less important. A longer pre-cooling period will decrease the peak cooling load but at the expense of greater energy use during the pre-cooling window
- Pre-cooling is not recommended in Climate Zone 3C (San Francisco, California) or Climate Zone 8 (Fairbanks, Alaska). There was no advantage from pre-cooling due to near-zero air conditioning use in these climates
- One caveat with the pre-cooling recommendations is that they are for lightweight wooden-framed homes. The recommendations may change for heavier brick/block structures not included in this study.

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